

*RESPONSE FORM, FORCE, AND NUMBER:  
EFFECTS ON CONCURRENT-SCHEDULE PERFORMANCE*

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Six hens responded on concurrent variable-interval (key-peck) variable-interval (door-push) schedules of reinforcement in which the second-order (fixed-ratio) requirements on the alternatives (Experiment 1) or the required door forces (Experiment 2) were varied. The key-peck and door-push response (measured as fixed-ratio completion) and time data were well described by the generalized matching law. However, the manipulations of fixed-ratio requirement and required response force differed in their effects. The manipulations of fixed-ratio size affected the response and time measures differently, producing fairly constant, multiplicative biases only in terms of response allocation. It was argued that variations in fixed-ratio size necessarily change the time allocated to that response unit, and thus changes in time bias were not necessarily a fundamental effect of changing the ratio. In contrast, the changes in response bias were a fundamental result of changes in ratio size. The response-force manipulations produced similar bias shifts in terms of response and time allocation, but they appeared to combine with relative reinforcement rate to affect choice interactively. Specifically, behavior appeared to be biased towards the least effortful (i.e., key-peck) response, but the increases in door force had a larger effect on bias when the hens were making this response infrequently (on a lean schedule). The different effects of the fixed-ratio and response-force manipulations on concurrent performance were partially accounted for by the differing times required to complete each response unit under those manipulations, but this would not account for the interaction. The interaction would be consonant with increased response effort decreasing the effective value of the associated reinforcement schedule.

*Key words:* concurrent schedules, second-order schedules, response form, response force, key peck, door push, hens

When investigating animals' choices, researchers generally offer outcomes differing in rate, magnitude, delay, and so on. The same type of response (usually key pecks with birds and lever presses with mammals) is typically used on the alternatives. In nonexperimental settings, however, different types of responses commonly lead to different outcomes.

Some findings have indicated that the study of different response requirements in laboratory settings would be informative. For example, researchers have reported difficulties in training animals to make particular responses for particular consequences (Dawkins & Beardsley, 1986; Hineline & Rachlin,

1969; Hogan & Roper, 1978). It has even been suggested that different behavioral laws may govern responses of different forms (Bolles, 1970; Seligman & Hager, 1972), or that the degree of influence of reinforcement over behavior may depend on the response-consequence pair chosen (Catania, 1973; Chelonis & Logue, 1996; Shettleworth, 1989).

Animal choice between similar responses arranged concurrently has been well described by the generalized matching law (Baum, 1979):

$$\log(B_1/B_2) = a \log(r_1/r_2) + \log c, \quad (1)$$

where  $B$  refers to the behavioral measure (responses made or times spent),  $r$  refers to the reinforcers obtained, and the subscripts denote two alternatives. The parameter  $a$  describes the sensitivity of behavior to reinforcement-rate differences, and the parameter  $c$  measures any constant preference for one alternative, over and above those from reinforcement-rate differences (Baum, 1974, 1979). Results from studies in which a variety of reinforcement schedules have been employed support the generality of this law (see Davison & McCarthy, 1988; de Villiers, 1977;

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Myers & Myers, 1977; Wearden & Burgess, 1982). The law has also been extended to situations in which qualitatively different reinforcers have been delivered on the two alternatives (Hollard & Davison, 1971; Matthews & Temple, 1979; Miller, 1976). It has only rarely been applied to choices in which response parameters have been varied.

Choice between different response requirements has been examined in three ways: (a) by using different response forms (Davison & Ferguson, 1978; Hanson & Green, 1986; McSweeney, 1978; Sumpter, Foster, & Temple, 1995; Wheatley & Engberg, 1978), (b) by changing the second-order requirements of second-order schedules (Beautrais & Davison, 1977; Cohen, 1975; Sumpter *et al.*, 1995), and (c) by varying the required force of the response (Chung, 1965; Hunter & Davison, 1982).

Apart from Sumpter *et al.* (1995), studies investigating the effects of different response forms have examined choice between one key peck and one treadle press over a range of reinforcement rates (Davison & Ferguson, 1978; Hanson & Green, 1986; McSweeney, 1978; Wheatley & Engberg, 1978). The results of these studies were well described by the generalized matching law, but performance was biased towards the key-peck requirement. The biases were particularly evident when performance was measured in terms of response rather than time allocation.

In the most extensive examination of the effects of required response force on concurrent variable-interval (VI) VI performance, Hunter and Davison (1982) varied the force required for an effective response by changing lead weights in pans attached to the keys. Sufficient conditions were arranged so that the relative and absolute effects of both response- and reinforcement-related variables could be assessed. Variations in both the reinforcement rates and the required forces changed preference considerably and similarly in terms of response and time measures. In addition, it was found that force requirement and reinforcement rate did not interact in their effects on relative response and time allocation.

Beautrais and Davison (1977) collected data from a series of concurrent second-order schedules in which completions of fixed-ratio

(FR) requirements were reinforced according to VI schedules. Both the FR requirements and the VI schedules were varied across conditions. When the FR requirements were equal, performance closely corresponded to that normally found when response requirements are single key pecks. There was no consistent bias, and the response and time sensitivities were not significantly different. In terms of response-unit (i.e., FR completion) measures, the changes in the second-order (FR) operants (i.e., from FR 5 vs. FR 5 to FR 5 vs. FR 10) resulted in shifts in bias towards the smaller FR requirement and increases in sensitivity. However, in terms of time allocation, the changes in neither bias nor sensitivity were significant.

Sumpter *et al.* (1995) varied both response form (key peck and door push) and FR requirements under concurrent second-order schedules of reinforcement. They found that when single responses were required, performance was biased towards the key alternative. They attributed this finding to the different amount of effort involved in the two response forms. When the number of key pecks required for a response unit was increased to five, bias shifted in the direction of the door alternative. Consistent with the results of Beautrais and Davison (1977), the change in the FR (key) requirement produced larger bias shifts in the FR completion measures than in the time measures. In the Sumpter *et al.* (1995) study, however, the resulting response and time biases were, on occasion, in different directions. In addition, the sensitivity of both behavior measures changed when the response requirements changed.

No simple generalizations on the effects of response parameters on concurrent performance seem possible. Force manipulations appear to produce similar changes in both response and time allocation (Hunter & Davison, 1982), whereas different response forms (Davison & Ferguson, 1978; McSweeney, 1978; Wheatley & Engberg, 1978) and changes in FR requirements of second-order schedules (Beautrais & Davison, 1977; Sumpter *et al.*, 1995) seem to affect time and response measures differently. Changes in second-order requirements also appear to affect sensitivity to reinforcement-rate changes, either in terms of both response and time allocation (Sumpter *et al.*, 1995) or in terms of

response allocation only (Beautrais & Davison, 1977), whereas force manipulations do not (Hunter & Davison, 1982). Sensitivity may be different for different response forms, but data are insufficient for any conclusions to be drawn.

The present experiments were designed to examine further the effects of three different response parameters (i.e., form, force, and number) on concurrent schedule performance. They were conducted in the hope of finding at least some commonality of effect.

### EXPERIMENT 1

Although Sumpter et al. (1995) varied the required number of responses in an operant unit with different response forms, they did so over a limited range. Specifically, they varied the relative reinforcement rates over the following response pairings: FR 1 (key) versus FR 5 (key); FR 1 (key) versus FR 1 (door); and FR 5 (key) versus FR 1 (door). They found that the generalized matching law described the data well and that, in terms of response-unit measures, variations in response type and number appeared to act as constant biases that could be multiplied to predict the bias term from the third pairing. Time biases, however, were not predicted from biases found in previous pairings.

The purpose of Experiment 1 was to extend Sumpter et al.'s (1995) findings by varying the FR requirements on both the key and door alternatives over a larger range, and to determine whether larger variations in required response number also provide constant bias measures within the generalized matching law. We also attempted to ascertain whether any observed differences in the FR completion and time-allocation data could be accounted for by response-duration effects, as Sumpter et al. argued. The same response types and all but one of the hens (Hen 66) employed by Sumpter et al. were used in order to provide direct comparisons.

#### *Method*

*Subjects.* Six Shaver-Starcross hens, numbered 61 to 66, were maintained at 80% ( $\pm 5\%$ ) of their free-feeding body weights through daily weighing and the provision of supplementary feed (commercial laying pellets). They were housed in individual cages

(30 cm by 45 cm by 43 cm) with water freely available. Grit and vitamins were supplied weekly. All hens were approximately 2.5 years old at the start of the experiment. Hens 61 to 65 had served in Sumpter et al.'s (1995) study and, in doing so, had experience on concurrent second-order (key-peck) (door-push) schedules of reinforcement. Hen 66 had been trained previously on a matching-to-sample key-peck task.

*Apparatus.* The particle-board experimental chamber was 57 cm long, 42 cm wide, and 54 cm high. A thick metal grid enclosed in a steel tray covered the floor, and a fan in the rear wall provided air circulation and masking noise. A food magazine, which was lit and allowed access to wheat when raised, was located directly behind an opening centered on the front wall 8.5 cm above the grid floor. The front wall also contained a Perspex key and a door response unit. The key, 3 cm in diameter, was situated 9.5 cm from the left wall and 36 cm above the floor. It required a minimum force of 0.1 N to be activated and, when operative, was lit from behind by a red 1-W bulb. The door apparatus, identical to that described by Sumpter et al. (1995), was located 2 cm from the right wall. It consisted of two vertical brass rods (through which the hens could push their heads and necks) which, when suspended, hung 4 cm inside the front wall and 10 cm above the grid floor. In order for an effective door push to be made, these rods needed to be pushed 5 cm forward (measured at the bottom of the rods) or to an angle of 15°. This movement operated a microswitch and required a minimum force of 1.1 N (112 g; measured 4 cm from the bottom of the rods) when no weights were attached to the door. The door returned to its vertical position under its own weight (i.e., as quickly as the hen backed away from it).

So that the hens did not hit the front wall when the rods were pushed to an angle of 15°, a hole (10 cm by 19 cm) was cut out of the front wall directly below the door frame and 11 cm from the floor. A box (10 cm wide, 18 cm deep, and 29 cm wide) was fixed to the rear of the front wall so that it covered the hole. This meant that the hen's head would be in this box when an effective door push was made. A 1-W white bulb located at the rear of this box provided illumination of

the door. The manipulanda lights and the magazine lights provided the only sources of illumination in the chamber. The equipment was controlled and the data were recorded by a computer operating MED<sup>®</sup> 2.0 software.

*Procedure.* Initially, the key was inoperative, and Hen 66 was trained to push the door by the hand-controlled delivery of reinforcement for successive approximations to the door-push response. Once the door-push response occurred reliably, a VI schedule was arranged for door pushes and was gradually increased to VI 30 s. Following this, the key was made operative. By Session 37, the VI schedules associated with both manipulanda had been increased to VI 90 s, and a changeover delay (COD) of 3 s was in effect (i.e., a response could not be reinforced until 3 s had elapsed from the first response on the changed-to schedule).

All birds were then exposed to a series of concurrent second-order (key-peck) (door-push) schedules of reinforcement, with responses that met the FR requirement reinforced according to VI schedules. During each part of the experiment, the FR requirements associated with the two manipulanda were kept constant while the VI schedules were varied across three conditions in the following order: concurrent VI 90 s VI 90 s, concurrent VI 60 s VI 180 s, concurrent VI 180 s VI 60 s. The VI schedules were arranged dependently (i.e., both VI schedules stopped timing when a reinforcer became available on either) and were composed of 15 randomized intervals that were derived from the arithmetic progression  $j(1 + 2x)$ , where  $x = 0, 1, 2, \dots, 14$  and  $j$  is equal to one 15th of the average VI length.

In Part 1, a single response on either manipulandum completed an FR 1 requirement, and if a reinforcer was arranged by the VI schedule associated with that manipulandum it was delivered. In Parts 2 and 3, FR requirements of 50 key pecks and two door pushes and 15 key pecks and three door pushes were required, respectively. The first response of each FR requirement (which could be emitted to either manipulandum) extinguished the alternative manipulandum light and rendered that manipulandum inoperative. On completion of the ratio requirement, and provided a reinforcer had been set up by the VI schedule associated with that manipulan-

dum, a reinforcer was delivered. Following reinforcement, or merely the completion of the FR requirement, both manipulanda lights were again presented.

In all parts of the experiment, each effective (i.e., first-order) response was signaled to the subject by a short (30-ms) audible beep, whereas the completion of each FR (second-order) requirement was signaled by a longer (0.4-s) audible beep. Reinforcement consisted of 3-s access to wheat if initiated by an FR completion on the key and 3.5-s access to wheat if initiated by an FR completion on the door. This gave the hens enough time to move back from the door and still get approximately 3-s access to the reinforcer. During reinforcement, the manipulanda lights were extinguished. Responses to unlit manipulanda were ineffective.

All experimental sessions ended after 30 reinforcers or 40 min (whichever was the shorter), and at least six sessions were conducted per week. The experimental parameters were changed when the behavior of all 6 subjects had met a stability criterion five, not necessarily consecutive, times. The criterion was that the median relative number of responses (i.e., total number of pecks on the key divided by the total number of responses to both manipulanda) over the last five sessions was within 0.05 of the median of the previous five sessions. Thus, a minimum of 14 sessions was required for stability. The sequence of experimental events along with the number of sessions each was in effect are shown in Table 1.

In all conditions, and for each response manipulandum, the following measures were recorded: the total number of responses (i.e., key pecks and door pushes), the number of post-COD responses, the total number of FR completions, the number of FR completions made within and after the CODs, the amount of time spent responding (timed, in seconds, from the first response on one manipulandum to the first response on the other), the number of reinforcers obtained, and the total number of changeover responses made.

### Results

The averages of the final five sessions' data from each condition are analyzed here, and the data from those last 5 days are presented in Appendix A. All ratios were taken to the left (key) alternative and are plotted on a log-

Table 1

The sequence of experimental conditions during Experiment 1. Shown are the FR and VI schedules in effect and the number of sessions in each condition.

Experimental part	Condition	FR schedules		VI schedules		Sessions
		Key	Door	Key	Door	
1	1	1	1	90	90	29
	2	1	1	60	180	17
	3	1	1	180	60	23
2	4	15	3	90	90	19
	5	15	3	60	180	18
	6	15	3	180	60	45
3	7	50	2	90	90	19
	8	50	2	60	180	21
	9	50	2	180	60	29

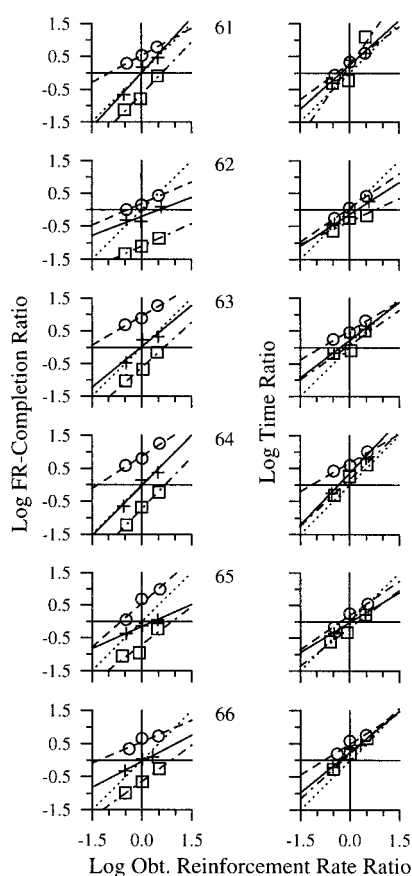


Fig. 1. The logarithms of the ratios of the FR completions (i.e., response units) made on each schedule (left panel) and the ratios of the times allocated to each schedule (right panel) as functions of the logarithms of the reinforcement-rate ratios. All ratios were taken to the left (key) alternative. The open circles, pluses, and open squares represent the data from Parts 1 (FR 1 vs. FR 1), 2 (FR 15 vs. FR 3), and 3 (FR 50 vs. FR 2) of Experiment 1, respectively. The dotted diagonal lines represent lines with a slope of 1.0. Other lines show least squares fits.

arithmetic scale (to the base 10). Unless otherwise stated, every completion of each FR requirement is regarded as an operant (i.e., FR completion) and is treated as a unit in these analyses.

The logarithms of the response-unit (i.e., FR completion) and time-allocation ratios obtained during all conditions are plotted for each hen against the logarithms of the obtained reinforcement-rate ratios in the left and right panels of Figure 1, respectively. Separate lines were fitted to the data from each part of the experiment, and the slopes ( $a$ ) and intercepts ( $\log c$ ) of the lines are shown in Table 2, together with the percentages of variance accounted for (%VAC) by the lines and the standard errors of estimate ( $SE$ ). The lines provide good descriptions of the data, as evidenced by the high %VAC values and the low  $SE$ .

The left panel of Figure 1 shows that every bird exhibited large response biases towards the key-peck requirement when only one response was required on each alternative. Increasing the FR requirement differential to FR 15 (key) versus FR 3 (door) during Part 2 decreased the response-unit biases (in terms of FR completions) to approximately zero for 4 hens. For the other 2 hens (Hens 62 and 65) these bias terms were substantially negative, indicating a bias towards the FR 3 (door-push) alternative. When the FR requirement differential was increased further to FR 50 (key) versus FR 2 (door), strong and systematic biases towards the FR 2 (door-push) alternative resulted. Thus, over the three experimental parts, the individual re-



Table 2

The slopes ( $a$ ) and intercepts ( $\log c$ ) of the lines fitted to both the response and time ratios from Experiment 1. All ratios were taken to the left (key) alternative. The percentages of the variance accounted for (%VAC) by the lines and the standard errors of the estimates ( $SE$ ) are also shown.

Hen	FR completions				Time allocation			
	$a$	$\log c$	%VAC	$SE$	$a$	$\log c$	%VAC	$SE$
Part 1: FR 1 (key) vs. FR 1 (door)								
61	0.55	0.54	100	0.00	0.74	0.29	100	0.06
62	0.44	0.19	98	0.04	0.69	0.06	83	0.00
63	0.59	0.96	96	0.08	0.59	0.51	97	0.07
64	0.65	0.87	97	0.09	0.58	0.67	95	0.09
65	0.90	0.56	94	0.17	0.70	0.19	98	0.07
66	0.43	0.56	84	0.11	0.62	0.49	92	0.11
$M$	0.59	0.61	95	0.08	0.65	0.37	94	0.07
Part 2: FR 15 (key) vs. FR 3 (door)								
61	1.11	0.00	95	0.18	0.91	0.24	94	0.16
62	0.39	-0.21	75	0.16	0.65	-0.14	98	0.07
63	0.83	0.02	84	0.25	0.77	0.22	97	0.09
64	1.01	-0.03	92	0.22	1.05	0.35	97	0.13
65	0.45	-0.16	100	0.02	0.61	-0.03	91	0.13
66	0.52	-0.03	94	0.08	0.82	0.24	95	0.11
$M$	0.72	-0.07	90	0.15	0.80	0.15	95	0.12
Part 3: FR 50 (key) vs. FR 2 (door)								
61	1.05	-0.64	97	0.13	1.44	0.22	81	0.49
62	0.45	-1.10	100	0.01	0.46	-0.35	88	0.13
63	0.92	-0.62	98	0.10	0.70	0.08	81	0.23
64	1.03	-0.73	99	0.07	0.94	0.17	97	0.12
65	0.77	-0.70	85	0.24	0.77	-0.20	98	0.09
66	0.73	-0.64	100	0.02	0.91	0.19	100	0.00
$M$	0.83	-0.74	97	0.10	0.87	0.02	91	0.18

sponse-unit biases moved from the key to the door.

The hens also exhibited time biases towards the key-peck requirement when only one response was required on both alternatives (Figure 1, right panel). For all hens, however, the time biases obtained during these conditions were smaller than the equivalent response-unit biases (Table 2). When the FR requirements on both alternatives were increased during Part 2 (FR 15 [key] vs. FR 3 [door]), all hens' time biases shifted in the direction of the door alternative. Again, for 2 hens (Hens 62 and 65) this resulted in a bias for the door. In Part 3, when the FR requirements were changed to FR 50 (key) versus FR 2 (door), the 2 hens that exhibited a bias for the door during Part 2 both showed an increase in bias in that direction. The data from the other 4 hens also showed bias changes towards the door but still exhibited small time biases for the key.

Table 2 indicates that only six of the 18

slopes describing the response data, and only four of those describing the time data, fall close to 1.00 (within the range 0.90 to 1.11). With the exception of one of the time-allocation slopes, the remainder are below 0.90. Although the magnitudes of these slopes appear to have increased from Part 1 to Part 3 (as shown by the mean  $a$  values calculated across subjects), this trend is not systematic within the individual data.

Figure 2 shows, for all hens, the logarithms of the number of changeovers made (per minute) plotted as functions of the logarithms of the obtained reinforcement-rate ratios. The changeover rates during Part 1 (FR 1 [key] vs. FR 1 [door]) tended to decrease as the reinforcement rate associated with the door decreased and that associated with the key increased. In Part 2 (FR 15 [key] vs. FR 3 [door]), the maximum rate of changing over typically occurred when equal VI schedules were programmed. In Part 3 (FR 50 [key] vs. FR 2 [door]), there was a general

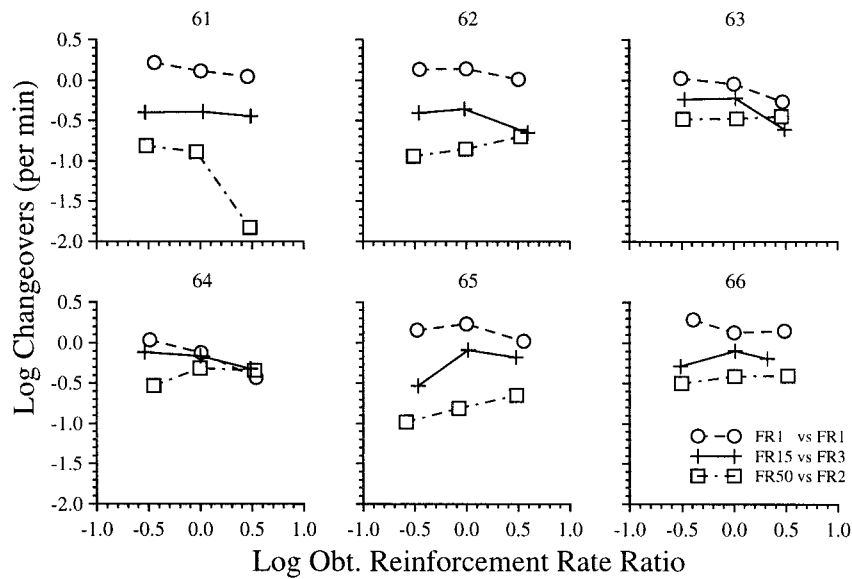


Fig. 2. The logarithms of the number of changeover responses made (per minute) during each part of Experiment 1 plotted against the logarithms of the ratios of the obtained reinforcement-rate ratios.

tendency (Hen 61 was the exception) for changeover rates to increase as the VI schedules associated with the door became leaner and as that associated with the key became richer.

#### Discussion

The response data from the FR 1 (key) versus FR 1 (door) conditions replicate the results of Sumpter et al. (1995). The average bias measure was 4.1:1, compared with the value of 4.5:1 reported by Sumpter et al. Thus, in terms of response measures, the hens' behavior was biased towards the key peck over the door push by about four to one.

Sumpter et al. (1995) found that increasing the FR requirement on the key from FR 1 to FR 5 abolished the 4.5:1 bias towards the door. Based on this result, they concluded that the bias towards the key was approximately 5.0. Hence, in this experiment, we would predict a slight bias towards the door when the FR requirement on the key is five times that on the door. As expected, when the FR requirements were changed to FR 15 (key) versus FR 3 (door), very small response biases (Table 2, Part 2, calculated as  $1/c$ , average 1:1.2) resulted. Bias towards the door of about 1:5 would be expected when the response-requirement differential moved to FR

50 (key) versus FR 2 (door). The average response bias measure obtained from the FR 50 (key) versus FR 2 (door) pairings was 1:5.5 (Table 2, Part 3, calculated from  $1/c$ ). Thus, as expected, the hens made about five times more FR 2 (door) response units than they did FR 50 (key) units. It appears, therefore, that bias produced by changes in FR requirements may be used to predict biases resulting from other FR requirement pairings, irrespective of response form.

The time-allocation data obtained during the FR 1 (key) versus FR 1 (door) conditions also approximately replicate the results obtained by Sumpter et al. (1995). Averaging across experiments gives a time bias measure of 2.6:1. This result suggests that when only one response is required, the hens spend about two and a half times longer on the key than the door but make about four times as many responses. Given that the move from FR 1 (key) versus FR 1 (door) to FR 15 (key) versus FR 3 (door) gave a shift in response-unit bias from about 4:1 (i.e., towards the key) to 1:1.2 (i.e., towards the door), it would be intuitive to expect a similar shift in the time biases. This was not found. The time-allocation biases moved in the expected direction, but for only 2 birds were the measures overall towards the door requirement (Table 2). The FR 50 (key) versus FR 2

(door) response requirements also produced different changes in the response-unit and time-allocation bias measures. Response-unit biases of 1:5.5 were found, but time-allocation biases approximated equality. Clearly then, the changes in the FR completion and time measures differ.

The differences in the response and time biases are consistent with data from other experiments that have employed topographically or numerically different response requirements. In all cases, the response-requirement differential produced a more extreme bias in the response measures than in the time measures (Beautrais & Davison, 1977; Davison & Ferguson, 1978; Hanson & Green, 1986; Sumpter *et al.*, 1995; Wheatley & Engberg, 1978).

There are several reasons why response and time measures would be expected to differ when response durations differ. Consider, for example, a choice between two alternatives, each requiring a single key peck. Because the response units are equal and take roughly the same amount of time, the response-unit and time biases tend to be equivalent (i.e., 1:1; assuming negligible bias from other sources). If response requirements are then changed to one key peck versus five key pecks (i.e., FR 1 vs. FR 5), one would generally get (i.e., Sumpter *et al.*, 1995) bias ratios of about 5:1 in terms of response (i.e., FR completion) measures and, again, bias ratios of approximately 1:1 in terms of times. In this case, response measures (i.e., completed response units) have shifted in a way that is predictable from the new second-order requirements (cf. Sumpter *et al.*, 1995), but time allocation has not. However, if we were to expect the time biases to follow the response biases (i.e., shift from 1:1 to 5:1), then one key peck would have to take about five times longer than a response unit of five key pecks (or the local response rate on the schedule requiring only one key peck as its unit would have to drop to one fifth of its previous value by increased pausing). Such changes are not commonly expected or observed.

As an example to illustrate, consider a hen responding on equal concurrent VI VI schedules of reinforcement. When single key pecks are required on each alternative, the ratios of the number of responses made, and of the times allocated, will be approximately 1:1. Let

us now arbitrarily define a response unit on the right alternative as a response requirement of five key pecks (i.e., an FR 5 key-peck requirement). The FR completion or response-unit bias would now be 5:1, but because the time allocated to responding has not changed, the time ratio will stay the same at 1:1. If the time bias were to change to 5:1, then either the hen would have to complete the FR 5 requirement five times faster than it would normally emit one key peck, or it would have to pause considerably on the alternative requiring the single key peck. It appears, therefore, that when response-unit requirements are changed, the only way that the time biases can follow the response biases would be for the durations of each response unit to shift in the opposite direction from the response-unit change. Hence, the time biases would not be expected to follow the response biases when second-order requirements of concurrent second-order schedules are changed.

Sumpter *et al.* (1995) used estimates, based on local response rates, of the response-unit durations from their first two response-unit pairings to predict the time biases for their third. This method was successful. When similar analyses are applied to the present data, however, the picture is less clear.

The average durations of a single key peck and a single door push were calculated for each bird and each part of the present experiment by averaging the inverse of the local response rates across the various reinforcement-rate conditions. These estimated durations include pause time and are given, along with the equivalent local response rates, in Table 3. Over the three parts of the experiment, the estimated durations of the first-order operants (and thus the local rates of responding on the alternatives) did not remain constant. The averaged local rates of key pecking were usually faster (duration estimates down), and the averaged rates of door pushing were usually slower (duration estimates up) in Part 3 than in Part 1. This trend was monotonic across the three experimental parts for 5 hens in door pushing but for only 3 hens in key pecking.

Because the local rates of responding were not constant over the FR requirement pairings, it is clear that Sumpter *et al.*'s (1995) predictions cannot be applied to the present



Table 3

The estimated average duration (in seconds) of a single key peck and a single door push for all experimental parts of Experiment 1. The equivalent local response rates (responses per minute) are shown in parentheses.

Hen	Key peck	Door push
Part 1: FR (key) FR 1 (door)		
61	2.12 (28.3)	3.89 (15.4)
62	3.01 (19.9)	4.08 (14.7)
63	1.36 (44.9)	3.58 (16.7)
64	1.34 (46.7)	2.12 (28.3)
65	1.53 (39.3)	3.48 (17.2)
66	1.75 (34.4)	1.98 (30.3)
Part 2: FR 15 (key) FR 3 (door)		
61	1.68 (35.7)	4.81 (12.5)
62	2.41 (24.9)	9.17 (6.5)
63	1.28 (46.9)	4.10 (14.6)
64	1.07 (56.1)	2.16 (27.8)
65	1.58 (37.8)	6.37 (9.4)
66	1.84 (32.5)	5.38 (11.2)
Part 3: FR 50 (key) FR 2 (door)		
61	3.27 (18.3)	9.62 (6.2)
62	2.36 (25.4)	10.42 (10.4)
63	1.04 (57.7)	4.93 (12.2)
64	0.97 (62.0)	3.08 (19.5)
65	1.44 (41.6)	12.50 (4.8)
66	1.29 (46.4)	5.05 (11.9)

data. However, Sumpter et al.'s analysis also raises another problem. It is difficult to conceive of discrete responses such as a key peck or a door push as taking more or less time to emit according to changes in second-order schedule requirements. The current changes in the local response rates must, therefore, reflect changes in either within-ratio or pre-ratio pausing across the FR requirement pairs. Hence, appealing though it is, Sumpter et al.'s analysis is probably of limited value.

The present study was not conducted to assess the effects of within- and across-component patterns of responding on concurrent second-order schedule performance. Thus, neither within-ratio nor pre-ratio pausing was measured. Nevertheless, studies of performance under second-order schedules (Findley, 1962; Kelleher, 1966; Lee & Gollub, 1971; Thomas & Stubbs, 1966) have shown that, when small FR requirements are employed, fairly constant response rates occur. In contrast, ratios between FR 40 and FR 80 yield maximum overall response rates (Lee & Gollub, 1971). On the basis of these results, one might have expected constant rates of re-

sponding on the door over the small range of FR sizes employed (i.e., FR 1 to FR 3). One might also have expected the local rates of key pecking to have increased when the FR requirement on the key increased to 50 if most of the pre-ratio pause time was allocated to the schedule associated with that FR. This increase was found for 5 birds. Thus, the existing data on second-order schedule performance may provide an explanation of the current response-rate changes.

The present data show undermatching in both FR completion and time measures, and support the proposition that undermatching in these measures is the norm (Davison & McCarthy, 1988). Values of  $a$  have been found to be between 0.8 and 1.0 for many species (Baum, 1979; Davison & McCarthy, 1988; Lobb & Davison, 1975; Myers & Myers, 1977), including hens (McAdie, Foster, & Temple, 1996; Temple, Scown, & Foster, 1995).

Previous studies using topographically different responses have also typically, but not exclusively, demonstrated undermatching. Davison and Ferguson (1978), Sumpter et al. (1995), and Wheatley and Engberg (1978) all reported undermatching for both responses and times. McSweeney (1978), in an examination of the effects of COD length (up to 20 s) on concurrent key-peck versus treadle-press performance, also reported undermatching. However, Hanson and Green (1986) obtained slopes close to 1.0 in their examination of concurrent key-peck versus treadle-press performance. Davison and Ferguson (1978) suggested that sensitivity may differ for different responses, but explaining the present undermatching this way adds little to the understanding of why undermatching occurs.

In this experiment arithmetic VI schedules were used, and the use of exponential schedules might have given less undermatching (Elliffe & Alsop, 1996). However, inspection of Elliffe and Alsop's data suggests that even the use of exponential schedules does not produce perfect matching. In addition, the range of sensitivities found here covered the range of sensitivity values reported by Elliffe and Alsop for both arithmetic and exponential schedules. It remains to be seen what effect exponential schedules would have in this case.

Baum (1974, 1979) suggested that undermatching might result from other procedural factors, such as the length of the COD, differences in deprivation levels, or the discriminability of stimuli. Assuming that, here, the alternative components were easily discriminable and the deprivation levels were not extraordinary, the changeover parameters seem a likely source of the undermatching found.

Wheatley and Engberg (1978) attributed their finding of undermatching to the use of a relatively brief 1-s COD. Davison and Ferguson (1978), using a slightly longer (2-s) COD, did find less extreme undermatching, and Hanson and Green (1986), using a 2.5-s COD, observed slopes close to 1.0. These findings suggest that the use of a 3-s COD, as was employed here, should have produced close approximations to matching. However, Temple *et al.* (1995) found little change (and some slight undermatching) for COD values between 2 and 15 s in their investigation of concurrent-schedule performance with hens, albeit with arithmetic schedules. This finding, along with McSweeney's (1978) failure to find matching using a 20-s COD, suggests that COD values longer than 3 s would not have produced slopes closer to 1.0.

Increasing the FR (key-peck) requirement during the second and third parts of the experiment made those response-unit durations longer than the programmed COD. Thus, there would have been no difference had we imposed no COD or CODs that were less than 3 s and different for each response requirement. It is tempting to attribute the increased sensitivity to this factor, but without more data it is hard to draw any conclusions regarding the separate or combined effects of response type, requirement, and duration, and of COD length on the degree of undermatching found.

Previously, changeover rates under concurrent schedules have been found to be maximal when the reinforcement rates are equal and to decrease with increasing disparity between the reinforcement rates (e.g., Baum, 1973, 1974; Brownstein & Pliskoff, 1968; Catania, 1963; Herrnstein, 1961; Stubbs & Pliskoff, 1969). Thus, when changeovers are plotted against relative reinforcer frequencies, an inverted U-shaped pattern is commonly observed. This pattern was consistently evident

in only Part 2 (FR 15 [key] vs. FR 3 [door]) of the present experiment (Figure 2).

That the changeover rates were not always maximal at equal reinforcer rates appears to be an anomalous finding. However, studies that give inverted U-shaped patterns have generally used the same response on both alternatives. In such cases, plotting changeover rate against reinforcement rate is equivalent to plotting the changeover rates against time allocation, because time allocation follows relative reinforcement-rate changes. In contrast, when different responses are employed, time allocation does not necessarily approximate equality at equal reinforcer rates. Thus, if the changeover rates obtained in each part of the present experiment were to be plotted against the relative times spent on the alternatives during those conditions, it is possible that the inverted U-shaped patterns will be observed with maximum changeover rates at equal time allocations. The log changeover-rate data are plotted for all hens against the log time-allocation ratios in Figure 3. It was expected that the functions presented in Figure 3 would show maxima at  $x$ -axis values close to zero, corresponding to maximum changeover rates with equal time allocation. Although this pattern is more apparent in Figure 3 than in Figure 2, it is not perfect. Nevertheless, for the monotonic trends (e.g., Hen 61 during the FR 1 vs. FR 1 conditions or Hen 62 for the FR 50 vs. FR 2 conditions) it seems clear that the transformation of the  $x$  axis has produced data that decrease with changes from zero. For the bitonic data the maximum changeover rates are still near zero. Thus, it appears that changeover patterns may be directly related to the relative times spent on the alternatives, not to the rates of reinforcement provided on those alternatives.

The rates of changing over also decreased as the FR requirement on the key increased and thus as the disparity between the two response requirements increased. It is possible that an asymmetry in the changeover delays was imposed by the arrangement that each changeover response reset the second-order (FR) requirements. Stubbs, Pliskoff, and Reid (1977) examined the effects of changeover delays on interchangeover time using the data from several other experiments. They reported that both asymmetrical changeover

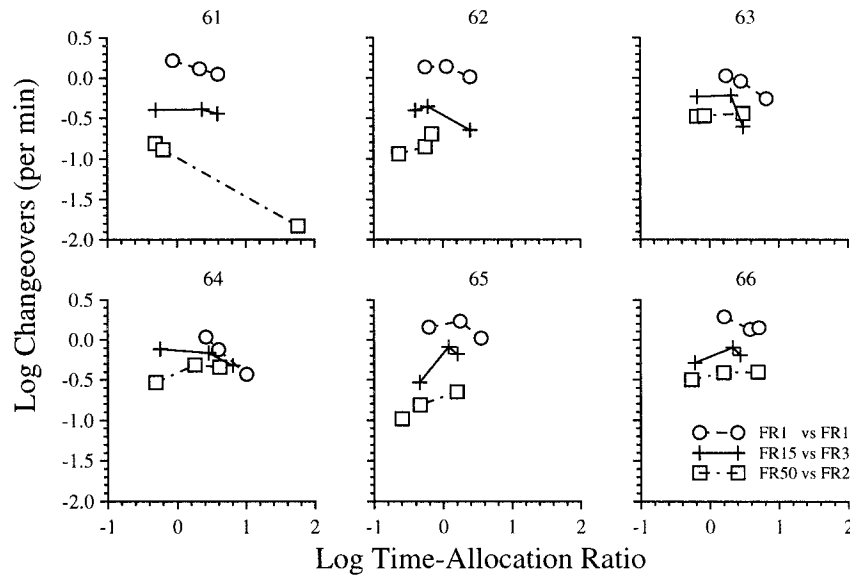


Fig. 3. The logarithms of the number of changeover responses made (per minute) during each part of Experiment 1 plotted against the logarithms of the time-allocation ratios.

delays and increasingly large FR changeover requirements increased interchangeover times and, therefore, decreased the rates of changing over. The systematic decrease in the changeover rates as the size of the FR on the key increased here suggests that the FR requirements may have acted as additional changeover requirements. There are some other data supporting this interpretation. In an examination of concurrent second-order VI  $x$ -s (fixed-interval 8-s) VI  $y$ -s (fixed-interval  $z$ -s) performance, Cohen (1975) also reported a systematic decrease in changeover rate as the varied second-order component ( $z$ ) increased. It is possible that because increasing the FR associated with the key reduced the overall reinforcement rates, this reduction may have contributed to the decreases in the changeover rates found. However, few studies examining concurrent second-order performance have included changeover data, and more data are necessary before any firm conclusion can be made.

## EXPERIMENT 2

In Experiment 1 only the second-order requirements of concurrent second-order schedules were varied. This might be regarded as varying the work or effort of each response unit. Another way to vary work would

be to vary the force required of each response.

The next experiment attempted to separate the effects of increases in response force and number by requiring only one response on each alternative and varying only the force required to push the door. These results can, therefore, be directly compared with those of Hunter and Davison (1982), who examined the effects of response-force manipulations on concurrent key-peck key-peck performance.

Part 1 of Experiment 1 provided data on concurrent FR 1 (key) FR 1 (door) performance with no additional force requirements over a range of reinforcement-rate pairs. To add confidence to the use of these data, the equal schedule condition was replicated.

### Method

*Subjects and apparatus.* The subjects from Experiment 1 served. The apparatus was identical to that used in Experiment 1.

*Procedure.* Throughout this experiment only one response was required on the key and door alternatives, and the force required to push the door was increased by adding a series of lead weights. In some conditions no weight was added, whereas in other conditions weights of 75 g, 150 g, and 300 g were added. The increments in door weight from

Table 4

The sequence of experimental conditions during Experiment 2. Shown are the variable-interval (VI) schedules (in seconds) associated with each alternative, the weights placed on the door, the forces required to emit a door push (both in grams force and newtons), and the total number of sessions in each condition.

Condition	VI schedules		Weight added (g)	Force		Sessions
	Key	Door		g force	N	
Part 1						
6	90	90	0	112	1.1	18
Part 2						
1	90	90	75	168	1.7	21
2	60	180	75	168	1.7	15
3	180	60	75	168	1.7	23
4	55.38	240	75	168	1.7	16
5	240	55.38	75	168	1.7	24
7	90	90	75	168	1.7	21
Part 3						
8	90	90	150	254	2.5	20
9	240	55.38	150	254	2.5	29
10	180	60	150	254	2.5	28
Part 4						
11	180	60	300	367	3.7	26

no weight to 300 g increased the required door force from 1.1 N to 3.7 N. The experimental conditions, the various force requirements, and the number of experimental sessions required to reach stability are shown in Table 4.

During the first series of conditions (Conditions 1 to 5), a 75-g weight was added to the door and the VI schedules were varied across those five conditions from concurrent VI 55.38-s VI 240-s schedules to concurrent VI 240-s VI 55.38-s schedules (Table 4). Following this, the birds participated in another study involving concurrent second-order (key-peck) (door-push) schedules in which a 75-g weight was added to the door. Conditions 6 to 11 of the present experiment were then conducted. In Conditions 6 and 7, the VI schedules were kept constant at VI 90 s, and no weight (Condition 6) or a 75-g weight (Condition 7) was added to the door. These conditions were, therefore, replications of Condition 1 of Experiment 1 and Condition 1 of this experiment. During Conditions 8 to 10, a 150-g weight was added to the door, and the VI schedules were varied over the three conditions from concurrent VI 90-s VI 90-s schedules to concurrent VI 240-s VI 55.38-s schedules. When exposed to the VI 90-s VI 90-s schedules with an additional 150-g door weight (Condition 8), 2 of the hens responded almost exclusively to the key (i.e., left) al-

ternative. Because of this, only disparate conditions favoring the door were conducted when a 150-g door weight was added to the door, because it was expected that no meaningful data would be gathered from the planned VI 60-s VI 180-s schedule condition. For the same reason, only one (concurrent VI 180-s VI 60-s) condition (Condition 11) was conducted when a 300-g weight was attached to the door. For ease of presentation, the sets of conditions involving the 0-g, 75-g, 150-g, and 300-g door weights will be referred to as Parts 1, 2, 3, and 4 (Table 4), even though this was not the order in which they occurred. All other aspects of the procedure were identical to those employed during Experiment 1.

### Results

The data analyzed here were averaged across the last 5 days of each condition and are presented in Appendix B. In Part 4, when the force required to push the door was high (i.e., 3.6 N), 2 birds (Hens 61 and 65) ceased responding. This result suggests that an effective, and perhaps the maximum feasible, range of response forces was covered.

The reliability of the hens' performances can be assessed by comparing the data obtained in Condition 6 of this experiment with those obtained in Condition 1 of Experiment 1 (VI 90-s VI 90-s schedules, no added door

Table 5

The log response- and time-allocation ratios for the replicated 0-g and 75-g door weight conditions. E1 represents Experiment 1, C1 represents Condition 1, and so on.

Hen	0-g door weight				75-g door weight			
	C1E1		C6E2		C1E2		C7E2	
	Response	Time	Response	Time	Response	Time	Response	Time
61	0.54	0.34	0.88	0.66	1.00	0.85	0.78	0.72
62	0.15	0.06	0.22	0.06	0.50	0.16	0.20	-0.01
63	0.89	0.46	0.98	0.42	0.83	0.51	1.01	0.40
64	0.80	0.60	0.98	0.57	1.09	0.64	0.97	0.60
65	0.69	0.25	1.20	0.54	1.38	0.70	0.81	0.38
66	0.65	0.58	0.47	0.33	0.79	0.70	0.60	0.31
<i>M</i>	0.62	0.38	0.79	0.43	0.93	0.59	0.73	0.40

weight), and by comparing the data obtained in Conditions 1 and 7 of the present experiment (VI 90-s VI 90-s schedules, 75-g door weight). Table 5 presents the response and time measures from these four conditions. It can be seen that replication produced inconsistent bias changes. With no additional door weight added (0-g conditions), the hens responded more on, and allocated more time to, the key (both relative measures increased in Table 5). With a 75-g door weight added, these bias changes were reversed (bias measures decreased in Table 5).

Because the data from the replicated 0-g and 75-g door-weight conditions were different from the original condition data, the individual data points from both the original and replicated conditions are included in the analyses. The data obtained during the unequal VI schedule FR 1 (key) versus FR 1 (door) conditions of Experiment 1 (i.e., in which the door was unweighted) are also included in the present analyses.

Figure 4 presents the logarithms of the ratios of responses and times as functions of the logarithms of the obtained reinforcement-rate ratios for all hens and sets of conditions. When there were enough data points, least squares regression lines were fitted to the data sets and are shown on the figures. The slopes ( $a$ ) and intercepts ( $\log c$ ) of these lines, together with the variances accounted for by the lines (%VAC) and the standard errors of estimate ( $SE$ ), are presented in Table 6. Again, the best fit lines describe the response and time data well. In general, the %VAC values are high (accounting for at least

80% of the data variance in 31 of 36 cases), and the standard errors of estimate are small.

Figure 4 shows that the lines describing the response data from the 150-g door-weight conditions are, in all cases, steeper than those describing the 0-g weight conditions. Although it is difficult to see these changes in the data in Figure 4 because the points and fitted lines overlap each other, inspection of Table 6 shows that for 4 hens (Hens 61, 63, 64, and 66) these changes in slope are monotonic across weights (i.e., the slopes of the lines describing the 75-g door-weight data are between those describing the 0-g and 150-g data). Similarly, five of the time-allocation slopes (the exception being Hen 61) increase over the 0-g to 150-g door-weight conditions, and these increases are monotonic for 3 of the 5 hens (Hens 63, 64, and 66). The points of intersection of all pairs of lines were examined, and in most cases (14 of the 18 response comparisons and 13 of the 18 time comparisons) the  $x$  values were negative (i.e., they intersect on the left side of the origin). Hence, the increases in slope arose largely from separation of the data at the right side of the figures (i.e., when the schedule arranged for the key was richer and that for the door was leaner), rather than from symmetric separations at both extremes of the graphs.

Table 6 also indicates that all but one of the response biases (the exception being Hen 63) and all of the time biases increased towards the key alternative over the change in door weight from no weight to 150 g. Again, however, these increases are not always monotonic across the 0-g, 75-g, and 150-g condi-



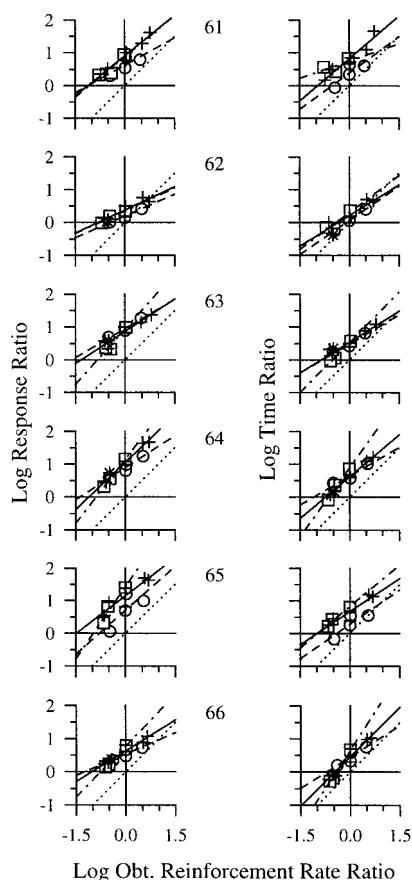


Fig. 4. The logarithms of the response-allocation (left panel) and time-allocation (right panel) ratios as functions of the logarithms of the reinforcement-rate ratios. All ratios were taken to the left (key) alternative. The open circles, pluses, open squares, and asterisks represent the data from the 0-g, 75-g, 150-g, and 300-g door-weight conditions of Experiment 2, respectively. For the 0-g door-weight conditions, the individual data points from the replicated VI 90-s VI 90-s points are shown, together with the data from the unequal schedule conditions conducted in Part 1 of Experiment 1. The individual data points from the replicated 75-g door-weight condition are also shown. The dotted diagonal lines represent lines with a slope of 1.0. Other lines show least squares fits.

tions. It should also be noted that when the response and time biases increase over the change in door weight from 75 g to 150 g, these increases are generally small. In addition, the 300-g door weight had no consistent effect on the response or time bias measures (log ratios) obtained during the VI 60-s VI 180-s schedule conditions (i.e., the asterisks are not clearly above the lines fitted to the 150-g data; Figure 4).

The effect of increasing the force requirement on the door in the presence of low as compared with high reinforcement rates is more clearly seen in Figure 5. Here the logarithms of the response and time ratios are plotted against door weight. The response and time ratios for the 150-g door weight with VI 60-s VI 180-s schedules were derived from the least squares lines fitting the individual 150-g door-weight data. When the VI schedule associated with the door was richest relative to that associated with the key (VI 240-s VI 55.38-s conditions; Panel 1), the response and time measures tended to decrease as door weight increased from 75 g to 150 g (i.e., they moved towards the door alternative). However, there were no consistent changes in either the response or time measures as door weight increased from 0 g to 300 g during the VI 180-s VI 60-s schedule conditions (Panel 2). During the equal schedule conditions (Panel 3), the response and time ratios tended to increase slightly in the direction of the key as the door weight increased. When the schedule associated with the door was lean (i.e., VI 60-s VI 180-s schedule conditions; Panel 4), there were larger and more systematic increases in these measures towards the key as the door weight increased to 150 g.

Figure 6 presents, for all hens, the logarithms of the absolute response rates on the key and the door plotted against door weight. During the VI 240-s VI 55.38-s schedule conditions (Panel 1), the increments in door weight from 75 g to 150 g decreased the absolute rates of key pecking, but they had no consistent effect on the absolute rates of door pushing. By contrast, the absolute rates of responding on both alternatives tended to decrease across the door-weight increases during the VI 180-s VI 60-s schedule conditions (Panel 2). Across the equal schedule conditions (Panel 3) no systematic changes in the absolute rates of key pecking were observed as door weight increased, but again the absolute rates of door pushing tended to decrease. When the VI schedule associated with the door was lean (VI 60-s VI 180-s schedule conditions), the absolute rates of responding on the key tended to increase while again those on the door typically decreased (Panel 4). The magnitudes of the differences in the absolute rates of key pecking and door push-

Table 6

The slopes ( $a$ ) and intercepts ( $\log c$ ) of the lines fitted to both the response- and time-allocation data from Experiment 2. The percentage of the variance accounted for by each line (%VAC) and the standard errors of estimate ( $SE$ ) are also shown.

Hen	Response allocation				Time allocation			
	$a$	$\log c$	%VAC	$SE$	$a$	$\log c$	%VAC	$SE$
Part 1: Parameters of the lines fitted to the data from the replicated no-weight VI 90-s VI 90-s schedule conditions (i.e., Condition 6 of Experiment 2 and Condition 1 of Experiment 1) together with the data from the unequal schedule (no-weight) conditions (Conditions 2 and 3) of Experiment 1.								
61	0.56	0.62	61	0.20	0.75	0.38	70	0.22
62	0.44	0.19	97	0.04	0.69	0.06	100	0.00
63	0.59	0.96	96	0.06	0.59	0.49	94	0.07
64	0.65	0.89	94	0.09	0.58	0.64	90	0.10
65	0.90	0.71	57	0.40	0.70	0.28	75	0.21
66	0.43	0.54	79	0.10	0.63	0.45	82	0.13
$M$	0.60	0.65	81	0.15	0.66	0.38	85	0.12
Part 2: Parameters of the lines fitted to the data from the replicated 75-g weight VI 90-s VI 90-s schedule conditions (i.e., Conditions 1 and 7 of Experiment 2) together with the data from the unequal schedule (75-g) conditions.								
61	0.82	0.91	97	0.10	0.86	0.82	93	0.15
62	0.47	0.38	82	0.13	0.62	0.21	83	0.17
63	0.66	0.86	90	0.14	0.63	0.55	91	0.12
64	0.95	1.05	98	0.09	0.85	0.62	99	0.05
65	0.78	1.16	80	0.24	0.68	0.67	85	0.17
66	0.62	0.64	94	0.09	0.99	0.46	94	0.15
$M$	0.72	0.83	90	0.13	0.77	0.56	91	0.14
Part 3: 150-g door weight								
61	0.83	0.89	82	0.20	0.35	0.75	41	0.23
62	0.46	0.35	93	0.07	0.75	0.30	86	0.16
63	1.13	0.94	93	0.14	1.02	0.54	99	0.04
64	1.30	1.15	100	0.01	1.39	0.89	97	0.12
65	1.48	1.44	91	0.23	0.85	0.83	96	0.09
66	1.03	0.78	100	0.01	1.52	0.65	100	0.04
$M$	1.04	0.93	93	0.11	0.98	0.66	87	0.11
Part 4: 300-g door weight								
61								
62		0.00				-0.36		
63		0.59				0.36		
64		0.73				0.17		
65								
66		0.37				-0.11		
$M$		0.42				0.02		

ing increased as the schedule associated with the key became richer and that associated with the door became leaner (compare Panels 1 to 4 of Figure 6). Thus, increased door force altered the hens' behavior to a larger extent when the leaner rate of reinforcement was arranged on the door.

The logarithms of the number of changeover responses made per minute on the key are plotted against door weight for all hens in Figure 7. The individual data points from the replicated equal schedule conditions are shown for the 0-g and 75-g door-weight con-

ditions. The changeover data from the unequal schedule 0-g weight conditions (i.e., from Part 1 of Experiment 1) are also included. In 17 of the 18 possible cases (i.e., those in which more than one schedule pair was conducted), the changeover rates were higher when the richer schedule was associated with the door than when the leaner schedule was associated with the door. This decrease was not, however, monotonic with door reinforcement rate. Regardless of the programmed reinforcement rates, rate of changing over tended to decrease as the door weight increased.

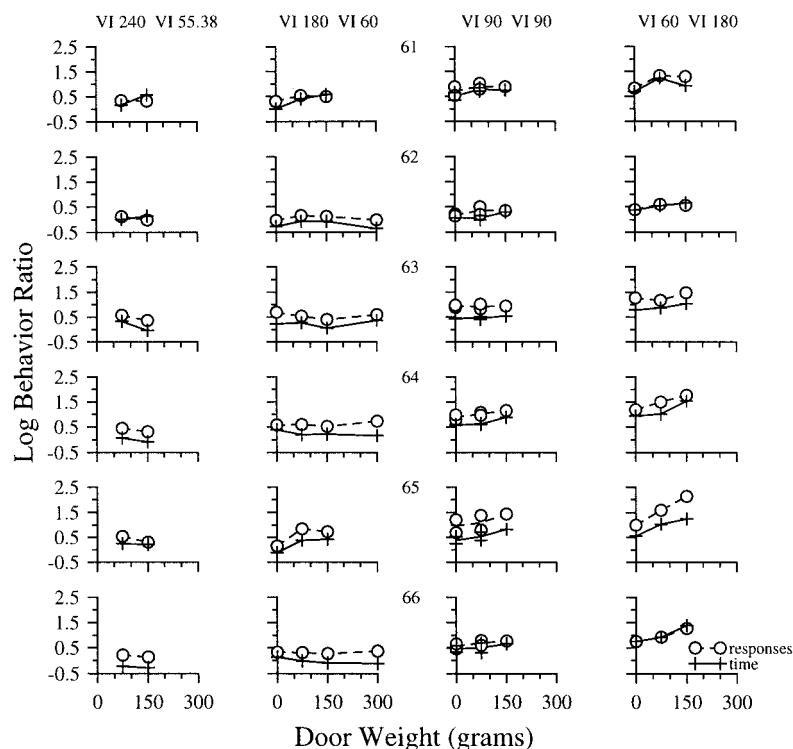


Fig. 5. The logarithms of the response (open circles) and time (pluses) ratios as functions of the weight placed on the door for all hens and reinforcement-rate conditions. For the 0-g and 75-g door-weight conditions, the data from the replicated VI 90-s VI 90-s points are shown. The data from the unequal schedule conditions conducted in Part 1 of Experiment 1 are also presented. The log behavior ratios expected to result from the 150-g door-weight conditions during exposure to the VI 60-s VI 180-s schedules (Panel 4) were derived from the lines fitting the 150-g data.

Figure 8 presents the log changeover-rate data for all birds and the various reinforcement-rate conditions plotted as functions of the log time-allocation data. Again, the individual data points from the replicated 0-g and 75-g door-weight conditions are shown, along with the changeover data from the unequal schedule 0-g door-weight conditions conducted during Part 1 of Experiment 1. Consistent with the results of Experiment 1, the rates of changing over tended to be highest when log time-allocation ratio approximated 0.0, and tended to decrease as relative time allocation became more extreme.

### Discussion

Increasing the weight added to the door affected the hens' behavior, but the effects of door weight appeared to vary across reinforcement-rate pairs. Several features of the data indicate this. First, the slopes of the lines

fitting both the response- and time-allocation data generally increased as door weight increased (Table 6). Second, inspection of Figure 4 suggests that, for most birds, the increases in the slopes had the effect of "pivoting" the lines about the left end (i.e., weight changes had less effect when the schedule on the door was rich and that on the key was lean). These differential changes can be seen more clearly in Figure 5 where, in Panels 1 and 2 (VI 240-s VI 55.38-s and VI 180-s VI 60-s conditions), there are no clear increases in the behavior ratios with increases in door weight. In Panel 3 (VI 90-s VI 90-s conditions), there is some tendency for the behavior measures to increase with increases in door weight, but these increases are more consistent in Panel 4 (VI 60-s VI 180-s conditions). The changes in the behavior ratios reflect changes in absolute response rates (Figure 6). The response rates on the key

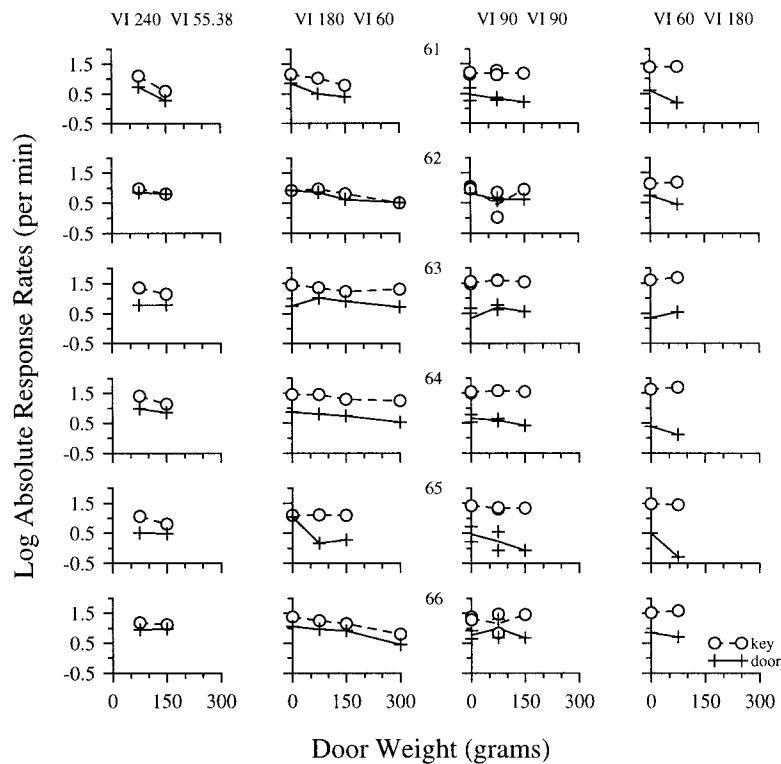


Fig. 6. The logarithms of the absolute response rates on the key (open circles) and the door (pluses) plotted against the weight placed on the door for all hens and reinforcement-rate conditions. The data from the replicated VI 90-s VI 90-s conditions are shown, together with the data from the unequal schedule conditions conducted in Part 1 of Experiment 1.

changed little with changes in door weight. The main changes in the absolute response rates came as reductions in door pushing in response to the door-weight increases. These changes were greatest when the schedule associated with the door was lean (Figure 6, Panels 3 and 4). When taken together, these results indicate that manipulations of response force may not act as constant sources of bias. Changes in door weight altered performance more when the schedule associated with the key was rich and that associated with the door was lean.

In hindsight, the observed interactions are consonant with the finding that the additional 300-g door weight had little effect relative to the 150-g door weight on the performances of the individual hens. Because 2 of the hens virtually stopped responding during the 150-g door-weight conditions, it was decided to assess the effects of an additional 300-g door weight only when the VI schedule associated with the door was rich and that as-

sociated with the key was lean. From the present analysis it is clear that had it been possible to obtain data with the 300-g weight added when the door schedule was lean, a greater effect might have been found.

One limitation in these data is the absence of replication in the latter part of this experiment. However, even those replications that were carried out pose a problem in interpretation. In the case of the 0-g weight conditions (a replication that occurred 3 years after original presentation), biases (both time and response) moved slightly towards the key. In the case of the 75-g weight conditions (replication over 4 months), both biases tended to move, but not for all subjects, away from the key. Because of the changes found, it may be best to conclude that no consistent alterations in bias occurred as a result of experience with the experiment. However, because no replications were conducted after the 150-g and 300-g door-weight conditions, it is still possible that there might have been some or-

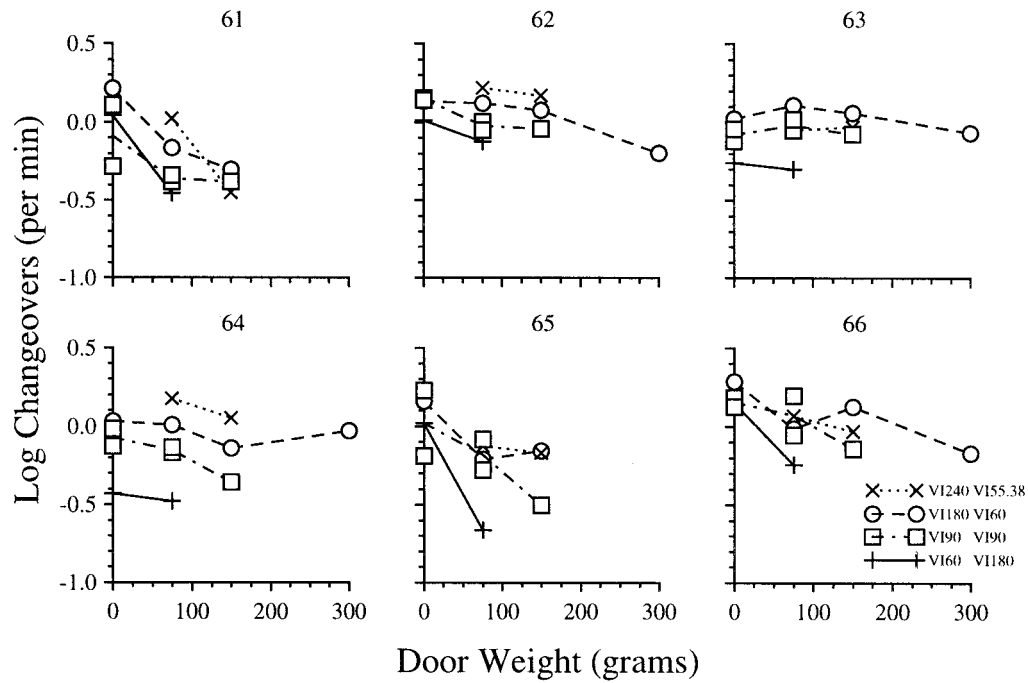


Fig. 7. The logarithms of the number of changeover responses made during each condition of Experiment 2 plotted for each hen against the weight placed on the door. The data for the replicated VI 90-s VI 90-s schedule conditions are shown, together with the data from the unequal schedule conditions conducted in Part 1 of Experiment 1.

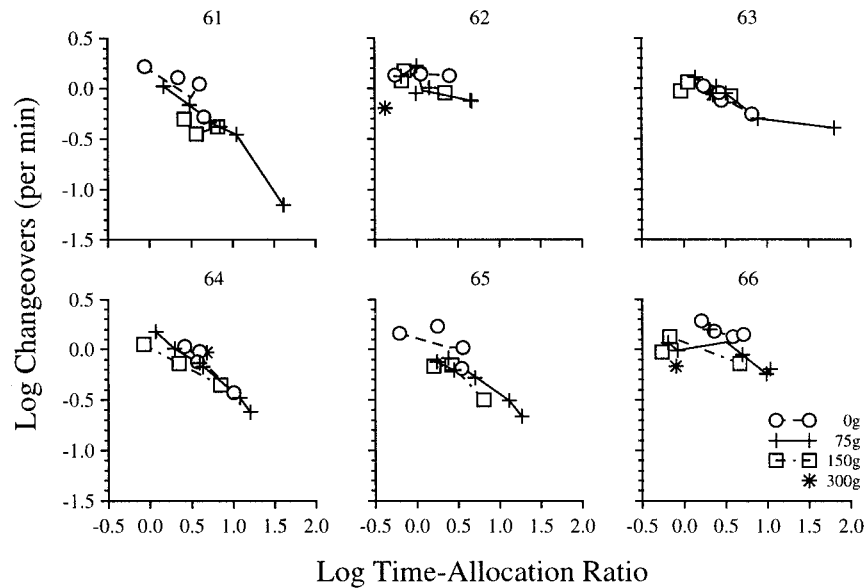


Fig. 8. The logarithms of the number of changeover responses made during each condition of Experiment 2 plotted for all hens against the logarithms of the time-allocation ratios.



der effect in the latter part of this experiment.

The finding that force-requirement and reinforcer-rate effects appear to combine to determine relative response and time allocation contradicts Hunter and Davison's (1982) report of independent effects of these variables. Hunter and Davison examined the effects of variations in required response force on concurrent key-peck key-peck performance. The interactions observed in the present study may have resulted from the use of a door-push response. However, Chung (1965) employed concurrent key-peck key-peck schedules of reinforcement and reported interactions between response-force and reinforcer-rate effects. Moreover, the results of Experiment 1 indicated that no consistent sensitivity changes were produced with increases in the FR requirements associated with both the key and the door. Thus, it appears unlikely that the current interactions were a product of the use of the door per se.

Hunter and Davison (1982) argued that the interactions observed in Chung's (1965) study may have arisen from relative reinforcer frequency changes rather than from the effects of required response force. Chung arranged independent concurrent VI VI schedules on the two keys, and some changes in obtained relative reinforcer frequency were observed with increasing force. In the present study, an attempt to control overall reinforcement rate and distribution was made by using dependent scheduling. However, when the schedule associated with the door was leaner, door-pushing rate decreased as the weight on the door increased and the overall rate of reinforcement decreased. Thus, the overall reinforcement-rate changes across conditions may have contributed to the interactions observed here.

The changeover-rate data obtained here were similar to those obtained in Experiment 1 (Figures 3 and 8). Rates were maximal when relative time allocation approximated equality and decreased as the time-allocation ratios became more extreme (i.e., moved away from 0.0). This finding supports the suggestion that changeover patterns reflect changes in time allocation, as opposed to changes in relative reinforcer rates, when different responses are employed.

The increases in force requirement, like

the increases in FR requirements employed in Experiment 1, decreased the rates of changing over. In both experiments (Figures 2 and 7), this trend was observed regardless of the relative reinforcement rates associated with the alternatives, and is likely due to increased response effort.

There are two general ways of viewing the possible effects of required response-force or response-effort changes. It was initially assumed that the effects of force increases might appear simply as constant bias terms in the generalized matching law (Equation 1). Hunter and Davison (1982) used a model in which the effects of different force requirements appeared as another ratio term raised to a power in the generalized matching law, similar to differing reinforcement rates. However, they found, and their model implies, no force and reinforcement-rate interactions. Thus, their model would not apply to the present data, because there appears to have been an interaction (Figures 4 and 5). The presence of an interaction suggests that response-force changes do not function simply as changes in response requirement (i.e., they do not simply change bias). An alternative explanation, suggested by Alling and Poling (1995), might be that increases in response force or response effort function as aversive events and reduce the value of the schedule of reinforcement. If the increases in force are thought of as punishing responding in some way, then they might be best regarded as subtracting from the effective reinforcement rates. If a given door-force requirement was considered to subtract a constant amount from the effective reinforcement rate, then it would have a greater effect on both schedule value and behavior when the reinforcement rate for door pushing was leaner. Such an analysis may account for the interaction observed here. It also predicts that even if equal schedules of reinforcement are programmed on the alternatives, they may not be of equal value when different response (or work) requirements are employed.

There are not enough data here to evaluate whether or not work requirements (i.e., FR and response-force requirements) subtract from the effective value of the reinforcement schedules that maintain them. However, such an interpretation is partially supported by the changeover-rate data. If

time allocation is taken as a reasonable reflection of the relative value of two schedules, then clearly changeover rates will be highest when time allocation is equal, which does not necessarily correspond to equal reinforcement rates (Figures 3 and 8). However, there may be a difference between the effects of a lower schedule value arising from a lower reinforcement rate and a lower schedule value resulting from an increased work requirement. Some features of the present data, especially the absolute response-rate changes found, bear on this possible difference. When reinforcement rate is lowered on one of two concurrent schedules, it is common for the absolute response rates to drop on that schedule and to increase on the other. Figure 6 shows that this increase did not happen here. Although the absolute rates of door pushing decreased, the absolute rates of key pecking remained approximately constant as the force required to push the door increased. Hence, the increase in response force seemed to act similarly to a reduction in schedule reinforcement rate, but the analogy is not perfect.

In summary, then, variations in response force and variations in response number were found to differ in their effects on concurrent key-peck door-push performance. Second-order (FR) schedule manipulations (Experiment 1) produced predictable biases in terms of both time and response allocation (i.e., completed response units). They did not appear to alter sensitivity to reinforcement rate. This was not true of manipulations of response force (Experiment 2). In contrast to Hunter and Davison's (1982) findings, the variations in relative response force appeared to interact with variations in relative reinforcer frequency to determine choice. The reason for the interaction is unclear but may lie in a similarity of response-force effects to the effects of overlaid punishers.

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## APPENDIX A

The sums of the data from the last 5 days of each condition of Experiment 1. The hen number (H), the experimental part (P), the condition number (C), the fixed-ratio (FR) schedules in effect on the left (L) and right (R) alternatives, the variable-interval (VI) schedules on the left (L) and right (R) alternatives, the total number of responses made on the left (RL) and right (RR) alternatives, the total time spent responding on the left (TL) and right (TR) alternatives, the number of reinforcements obtained on the left (rL) and right (rR) alternatives, the number of responses made during the changeover delays (WCOD) on the left (L) and right (R) alternatives, the number of changeover responses (CO) from the left (L) and right (R) alternatives, the total number of completed FR requirements (COMFR) made on the left (L) and right (R) alternatives, the number of completed FR requirements made after the changeover delays (FR PCOD) on the left (L) and right (R) alternatives, and the total session time (time).

H	P	C	FR		VI		RL	RR	TL	TR	rL	rR	WCOD		CO		COMFR		FR PCOD		Time
			L	R	L	R							L	R	L	R	L	R	L	R	
61	1	1	1	1	90	90	3,042	877	7,623	3,476	67	66	641	465	243	241					11,366
61	1	2	1	1	60	180	4,088	676	7,934	1,981	111	39	573	327	186	184					10,116
61	1	3	1	1	180	60	2,282	1,147	4,415	5,012	40	110	969	403	269	266					9,705
61	2	1	15	3	90	90	4,486	672	8,283	3,499	60	56	253	108	81	82	324	224	324	188	12,000
61	2	2	15	3	60	180	5,975	462	9,219	2,366	98	33	159	94	71	74	397	154	397	126	11,807

## APPENDIX A

(Continued)

													FR								
FR				VI									WCOD		CO		COMFR		FR PCOD		
H	P	C	L	R	L	R	RL	RR	TL	TR	rL	rR	L	R	L	R	L	R	L	R	Time
61	2	3	15	3	180	60	1,874	1,673	3,874	7,652	32	108	149	174	78	78	124	557	124	498	11,635
61	3	1	50	2	90	90	2,078	459	4,543	7,106	27	32	28	81	31	32	41	229	41	180	12,000
61	3	2	50	2	60	180	1,448	22	9,632	167	9	1	1	7	3	3	26	11	26	6	12,000
61	3	3	50	2	180	60	1,998	1,088	3,869	7,845	22	74	26	80	33	33	39	544	39	497	12,000
62	1	1	1	1	90	90	1,566	1,106	5,345	4,701	74	74	395	514	238	234					10,336
62	1	2	1	1	60	180	2,222	870	6,696	2,649	114	36	249	457	164	163					9,528
62	1	3	1	1	180	60	1,321	1,304	3,366	6,026	39	111	352	499	218	216					9,624
62	2	1	15	3	90	90	2,074	1,010	4,523	7,325	58	61	99	146	88	86	137	336	137	290	12,000
62	2	2	15	3	60	180	2,937	322	8,538	3,367	64	15	36	49	45	44	194	107	194	94	12,000
62	2	3	15	3	180	60	1,791	743	3,349	8,358	33	96	54	113	78	79	119	247	119	211	11,935
62	3	1	50	2	90	90	1,839	701	4,225	7,490	26	27	9	46	28	32	28	350	28	320	12,000
62	3	2	50	2	60	180	2,139	610	4,736	6,785	38	12	21	30	40	42	42	305	42	287	12,000
62	3	3	50	2	180	60	1,178	986	2,255	9,684	20	64	10	38	23	25	23	492	23	470	12,000
62	1	1	1	1	90	90	6,068	777	7,354	2,576	75	75	691	210	153	148					10,097
62	1	2	1	1	60	180	6,854	376	8,856	1,336	109	37	381	144	94	93					10,307
63	1	3	1	1	180	60	5,071	1,034	6,820	3,930	36	114	1,036	330	193	190					10,964
63	2	1	15	3	90	90	6,851	801	7,614	3,688	71	69	407	158	114	114	456	267	456	217	11,440
63	2	2	15	3	60	180	5,249	500	8,860	2,907	75	26	118	100	49	49	348	166	348	132	12,000
63	2	3	15	3	180	60	3,368	1,947	4,496	6,725	37	109	300	154	110	110	224	649	224	598	11,355
63	3	1	50	2	90	90	5,588	943	5,396	6,326	50	50	128	141	67	66	111	471	111	386	12,000
63	3	2	50	2	60	180	8,220	488	8,971	2,916	80	28	228	140	72	74	164	244	164	156	12,000
63	3	3	50	2	180	60	4,439	1,868	4,615	6,994	36	110	210	185	65	66	88	934	88	826	11,701
64	1	1	1	1	90	90	6,488	1,043	8,379	2,103	73	73	385	560	131	129					10,612
64	1	2	1	1	60	180	7,602	443	9,769	957	113	33	269	217	67	66					10,799
64	1	3	1	1	180	60	5,194	1,353	7,752	2,956	37	113	778	702	195	192					10,915
64	2	1	15	3	90	90	8,223	1,219	8,219	2,886	73	73	420	393	128	124	548	406	548	278	11,244
64	2	2	15	3	60	180	8,250	729	9,177	1,464	108	36	474	234	85	84	550	243	550	168	10,745
64	2	3	15	3	180	60	3,240	3,042	3,694	6,418	33	114	765	314	130	128	216	1,014	216	915	10,267
64	3	1	50	2	90	90	8,663	1,596	7,621	4,198	64	65	112	124	96	98	171	798	171	314	11,938
64	3	2	50	2	60	180	8,874	646	9,552	2,319	100	31	182	141	91	92	190	323	190	91	11,993
64	3	3	50	2	180	60	3,500	2,421	3,892	7,830	36	102	186	95	58	57	70	1,210	70	251	11,804
65	1	1	1	1	90	90	3,892	808	5,633	3,173	75	75	1,030	170	258	253					9,073
65	1	2	1	1	60	180	4,618	481	6,973	1,947	117	33	577	105	159	158					9,106
65	1	3	1	1	180	60	2,031	1,801	3,796	5,638	38	112	773	208	233	231					9,689
65	2	1	15	3	90	90	3,885	1,083	5,695	4,715	76	74	165	92	145	145	259	361	259	347	10,583
65	2	2	15	3	60	180	4,620	837	6,535	4,061	112	38	135	92	118	121	308	279	308	260	10,755
65	2	3	15	3	180	60	1,534	728	3,692	8,110	29	86	111	27	59	61	101	242	101	237	12,000
65	3	1	50	2	90	90	2,056	744	3,757	8,012	29	35	14	17	31	31	41	371	41	356	12,000
65	3	2	50	2	60	180	5,903	428	7,252	4,595	60	19	60	22	45	44	117	214	117	193	12,000
65	3	3	50	2	180	60	1,330	590	2,395	9,419	18	69	17	4	21	22	26	294	26	290	12,000
66	1	1	1	1	90	90	3,252	741	7,947	2,070	75	75	257	300	228	224					10,257
66	1	2	1	1	60	180	5,341	1,134	7,979	1,550	113	37	734	540	228	227					9,769
66	1	3	1	1	180	60	3,922	1,089	5,903	3,684	43	105	978	926	318	316					9,926
66	2	1	15	3	90	90	4,710	859	7,506	3,452	75	74	557	293	150	145	314	285	314	192	11,335
66	2	2	15	3	60	180	3,808	631	8,264	2,979	96	47	568	148	124	122	253	210	253	164	11,613
66	2	3	15	3	180	60	2,295	972	4,181	6,810	34	109	291	131	96	95	153	324	153	285	11,301
66	3	1	50	2	90	90	5,337	939	7,211	4,547	54	53	149	286	78	81	105	469	105	310	12,000
66	3	2	50	2	60	180	8,343	592	9,613	2,143	107	33	152	245	78	82	166	296	166	157	11,899
66	3	3	50	2	180	60	3,343	1,295	4,166	7,579	31	98	150	138	63	65	66	647	66	561	11,912

## APPENDIX B

The sums of the data from the last 5 days of each condition of Experiment 2. The hen number (H), the experimental part (P), the condition number (C), the variable-interval (VI) schedules on the left (L) and right (R) alternatives, the total number of responses made on the left (RL) and right (RR) alternatives, the total time spent responding to the left (TL) and right (TR) alternatives, the number of reinforcements obtained on the left (rL) and right (rR) alternatives, the number of responses made during the changeover delays (WCOD) on the left (L) and right (R) alternatives, the number of changeover responses (CO) from the left (L) and right (R) alternatives, the number of responses made after the changeover delays (PCOD) on the left (L) and right (R) alternatives, and the total session time (Time). Hens 61 and 65 did not complete Part 4 of this experiment.

H	P	C	VI		RL	RR	TL	TR	rL	rR	WCOD		CO		PCOD		Time
			L	R							L	R	L	R	L	R	
61	1	6	90	90	2,806	372	9,610	2,140	53	50	241	189	103	102	2,563	183	12,000
61	2	1	90	90	3,692	385	10,357	1,518	61	55	131	193	82	83	3,561	192	12,000
61	2	2	60	180	4,892	297	10,574	944	92	29	193	163	67	67	4,699	134	11,630
61	2	3	180	60	2,059	611	8,714	2,884	26	82	308	326	137	137	1,751	285	12,000
61	2	4	55.38	240	2,463	64	11,687	286	65	12	28	38	14	13	2,435	26	12,000
61	2	5	240	55.38	2,386	1,051	6,761	4,549	22	116	726	485	202	202	1,657	564	11,551
61	2	7	90	90	2,708	465	9,924	1,920	59	56	288	141	92	91	2,419	324	12,000
61	3	8	90	90	3,013	337	10,251	1,551	35	35	206	189	83	83	2,807	148	12,000
61	3	9	240	55.38	777	372	9,298	2,545	10	59	102	162	71	70	675	210	12,000
61	3	10	180	60	1,219	497	8,507	3,279	21	53	201	260	99	98	1,018	237	12,000
62	1	6	90	90	1,827	1,102	5,125	4,496	75	75	243	507	234	234	1,584	592	9,876
62	2	1	90	90	2,182	692	6,540	4,544	74	72	250	324	190	188	1,932	368	11,331
62	2	2	60	180	2,675	479	8,312	1,778	106	33	101	254	126	124	2,571	225	10,262
62	2	3	180	60	1,532	1,221	3,940	6,015	35	115	260	549	225	220	1,271	666	10,318
62	2	4	55.38	240	2,401	557	7,619	1,695	126	24	114	293	120	119	2,286	264	9,452
62	2	5	240	55.38	1,700	1,259	5,181	5,168	29	121	311	577	298	294	1,388	682	10,759
62	2	7	90	90	1,259	786	5,155	5,223	75	75	103	158	155	153	1,156	628	10,587
62	3	8	90	90	1,671	758	7,655	3,410	72	69	166	432	170	166	1,505	326	11,317
62	3	9	240	55.38	1,151	1,162	4,369	6,109	25	125	185	440	269	265	966	719	10,860
62	3	10	180	60	1,219	771	4,423	6,683	37	107	224	248	227	226	995	522	11,448
62	4	11	180	60	620	632	3,354	7,913	36	112	88	178	123	121	532	454	11,654
63	1	6	90	90	5,684	609	8,124	3,056	70	71	513	171	143	144	5,170	438	11,371
63	2	1	90	90	7,218	1,057	7,879	2,454	75	75	661	501	155	152	6,557	556	10,504
63	2	2	60	180	8,931	643	9,768	1,251	109	37	290	384	92	92	8,641	259	11,143
63	2	3	180	60	3,788	1,749	5,648	4,080	35	115	962	604	214	213	2,826	1,145	9,980
63	2	4	55.38	240	10,084	435	9,467	786	129	21	300	162	69	69	9,784	273	10,339
63	2	5	240	55.38	4,346	1,154	7,604	3,633	28	115	849	420	171	169	3,497	734	11,467
63	2	7	90	90	6,844	706	7,177	2,859	71	73	912	162	175	174	5,932	543	10,253
63	3	8	90	90	6,532	679	8,737	2,381	65	63	772	209	157	155	5,760	470	11,322
63	3	9	240	55.38	2,516	1,073	5,103	5,497	31	118	702	208	169	171	1,814	865	10,850
63	3	10	180	60	2,739	1,283	5,044	4,439	40	110	876	261	187	186	1,863	1,022	9,743
63	4	11	180	60	3,926	1,014	8,010	3,542	35	107	726	418	168	168	3,200	596	11,784
64	1	6	90	90	6,089	639	8,636	2,358	77	73	671	212	178	175	5,414	427	11,189
64	2	1	90	90	7,228	677	9,007	2,148	73	73	452	162	127	123	6,775	514	11,286
64	2	2	60	180	10,201	255	10,862	896	108	33	281	83	65	65	9,920	171	11,828
64	2	3	180	60	5,162	1,126	7,153	3,612	38	111	597	365	184	180	4,565	761	11,023
64	2	4	55.38	240	8,954	213	9,813	607	125	24	147	54	41	41	8,807	159	10,476
64	2	5	240	55.38	4,061	1,503	5,083	4,282	31	119	932	377	237	232	3,129	1,126	9,654
64	2	7	90	90	6,089	639	8,636	2,358	77	73	671	212	178	175	5,414	427	11,189
64	3	8	90	90	7,092	519	10,266	1,448	61	61	322	294	87	85	6,770	225	11,865
64	3	9	240	55.38	2,328	1,158	4,493	5,325	28	122	488	215	188	185	1,839	941	10,082
64	3	10	180	60	3,857	1,081	7,978	3,563	38	107	386	453	141	139	3,471	628	11,718
64	4	11	180	60	3,210	615	6,369	4,330	38	111	542	69	169	164	2,665	545	10,887
65	1	6	90	90	5,054	318	8,878	2,593	68	65	432	22	125	122	4,622	295	11,599
65	2	1	90	90	4,070	169	9,864	2,026	42	42	271	12	105	105	3,795	156	12,000
65	2	2	60	180	5,605	97	11,129	605	90	24	142	2	42	42	5,460	92	11,789



## APPENDIX B

(Continued)

H	P	C	VI		RL	RR	TL	TR	rL	rR	WCOD		CO		PCOD		Time
			L	R							L	R	L	R	L	R	
65	2	3	180	60	2,641	296	8,695	3,101	30	95	304	8	124	125	2,335	287	12,000
65	2	4	55.38	240	5,795	187	10,460	810	116	24	158	77	57	57	5,632	110	11,341
65	2	5	240	55.38	2,316	666	7,531	4,290	25	111	369	60	150	149	1,946	604	12,000
65	2	7	90	90	4,179	652	7,639	3,193	75	75	555	234	151	146	3,618	415	10,988
65	3	8	90	90	4,267	172	10,297	1,605	55	55	171	7	63	63	4,096	165	12,000
65	3	9	240	55.38	1,237	593	7,027	4,379	26	116	262	52	130	127	975	541	11,556
65	3	10	180	60	2,496	381	8,603	3,235	30	102	312	3	140	139	2,184	378	12,000
66	1	6	90	90	3,649	1,226	6,009	2,847	75	75	1,044	571	232	230	2,601	654	9,137
66	2	1	90	90	5,652	927	9,299	1,891	72	72	841	574	167	163	4,807	353	11,470
66	2	2	60	180	6,081	806	8,641	896	108	33	439	579	90	89	5,642	227	9,666
66	2	3	180	60	2,839	1,493	4,296	5,161	34	116	878	530	216	213	1,960	959	9,699
66	2	4	55.38	240	7,954	684	8,474	789	122	28	557	421	99	98	7,389	236	9,373
66	2	5	240	55.38	2,371	1,401	3,684	5,687	26	116	1,006	377	184	184	1,365	1,024	9,643
66	2	7	90	90	4,114	1,035	5,944	2,911	75	75	1,090	388	239	236	2,996	642	9,112
66	3	8	90	90	5,255	871	8,994	1,938	71	70	581	481	132	129	4,674	390	11,097
66	3	9	240	55.38	2,121	1,525	3,322	6,147	29	121	600	362	151	153	1,521	1,162	9,680
66	3	10	180	60	2,369	1,371	4,011	5,970	35	115	576	314	165	164	1,793	1,057	10,218
66	4	11	180	60	1,215	532	5,040	6,321	37	101	367	98	130	128	848	434	11,562